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Research article

Ecological validity of experimental set-up affects parietal involvement during letter production

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ABSTRACT

Studies of symbol production using fMRI often use techniques that introduce an artificial pairing between motor production and visual perception. These techniques allow participants to see their own output by recording their pen trajectories using a touchscreen-only tablet and displaying these productions on a mirror placed above their head. We recently developed an MR-safe writing tablet with video display that allows participants to see their own hand and their own productions while producing symbols in real time on the surface where they are producing them—allowing for more ecologically valid fMRI studies of production. We conducted a study to determine whether the participation of posterior parietal cortex during symbol production was affected by the pairing of motor production and visual feedback associated with the two types of tablets. We performed ROI analyses in intraparietal sulcus while adult participants produced letters to dictation using either a touchscreen-only tablet (no visual guidance of the hand) (n = 14) or using a touchscreen-and-video-display tablet (visual guidance of the hand) (n = 14). We found that left posterior intraparietal sulcus was more active during production with the touchscreen-only tablet than during production with the touchscreen-and-video-display tablet. These results suggest that posterior parietal involvement during production tasks is associated with the somewhat artificial visual-motor pairing that is introduced by the techniques used in some studies of symbol production.

1. Introduction

The neural mechanisms underlying production tasks, such as drawing and handwriting, have often been studied using experimental set-ups that allow participants to see neither what they are writing nor their own hands during production. Participants have traditionally been asked to focus their visual attention on a fixation cross while they draw/write with their finger in the air (e.g., [9]) or on a paper tablet by their waist (e.g., James & Gauthier, 2006; [1,11,18]). More recent set-ups incorporate touchscreen-only surfaces that record the position of the pen during production either through the use of sensors that track the position of a stylus on a digitizing surface [13,20] or through the pairing of a light emitting stylus and a surface with color-coded locations [3,17]. Pen trajectories can easily be recorded, replayed, and projected onto a mirror above the participant's head to allow participants to see what they are writing and have been used in several studies focused on specifying the neural mechanisms supporting production (e.g., [5,6,12,21,22,25]).

MR-safe touchscreen-only surfaces are useful for some experimental questions because they allow for a clean separation between the visual experience of one's hand from the visual experience of the form being produced. Hand movements occur on the touchscreen surface near the participant's torso while the visual feedback of the form being produced is displayed on a mirror above their head. Researchers can, for example, manipulate the visual feedback of the form being produced without the confound of the visual feedback of the participant's hand during production. While this is an advantage for some studies, it is a disadvantage for others. A direct pairing between visual feedback of the form and of one's hand is a fundamental aspect of production that is important in certain populations (e.g., young children) and for several research programs (e.g., visual-motor integration, spatial attention, drawing complex figures).

Some studies have developed methods that provide visual feedback of one's own hand positions relative to the visual feedback of the form being produced, yet none of these methods provide the visual feedback of one's hand and the form being produced at the location where it is being produced. The motor movements, in other words, occur at a different location than the visual feedback. Karimpoor et al. [7,8] developed a method for displaying a hand avatar holding a pen as a part of the visual feedback provided in the mirror during production to

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study the neural mechanisms that support a common executive functioning task. In another approach, Shah et al. [19] used a series of mirrors to project an egocentric view of the hand and the form being produced onto the mirror above the participant's head to study the neural mechanisms associated with creative writing and brainstorming. Neither study focused on production, however, and neither method was able to provide a direct, ecologically valid pairing between the motor movements (i.e., the motor component of production) and the visual experience of the hand moving and the form being produced (i.e., the visual components of production). In both approaches, the participant must translate between the visual feedback presented in the mirror and their proprioceptive feedback of their hand near their torso.

We have recently developed a device and technique that provides a more ecologically valid coupling between the motor and visual components of production during fMRI scanning (see Fig. 1). The "MRItab" differs from the prior tablet/projection methods because it can display what is being drawn in real-time as the subject is producing it *on the tablet surface* [24]. We have also developed a holding apparatus that allows the participant to look directly at the tablet. As such, the participant is able to see what they are writing and their own hands during production—just as they would outside of the MRI environment—without the need to resolve any conflicts between visual and proprioceptive feedback concerning where their hand is in space.

1.1. Parietal Involvement in Production Tasks

Recent studies using touchscreen-only tablets have suggested that left anterior intraparietal sulcus is strongly associated with the motor component of production while left posterior intraparietal sulcus is strongly associated with the visual component of symbol production. Two meta-analyses that were conducted prior to the availability of touchscreen-only tablets did not, however, report the involvement of the posterior parietal cortex during production tasks [15,16].[1] We were interested to discover whether this discrepancy in findings was due to the relative ecological validity of various production tasks.

1.1.1. Anterior intraparietal sulcus

Both meta-analyses report loci in anterior parietal cortex, specifically the left superior parietal lobe and left anterior intraparietal sulcus (LaIPS), during production tasks [15,16]. Recent research using touchscreen-only tablets suggest similar anterior parietal involvement: First, activation in the LaIPS (and motor cortex) during production without visual feedback can be used to decode letter identity [5,6]. Second, activation in LaIPS (and motor cortex) was greater during production with visual feedback compared to passive visual perception of a form produced unfolding as if it were being produced [22]. The statement that anterior parietal involvement is strongly related to the motor movements required during production is, therefore, supported by the results of two meta-analyses as well as recent work using touchscreen-only tablets.

1.1.2. Posterior intraparietal sulcus

Neither meta-analyses report loci in posterior parietal cortex [15,16], though recent work using touchscreen-only writing tablets report posterior parietal involvement related to the use of visual guidance during production. First, LpIPS was more active when participants were provided with a visual prompt concerning the spatial location of their hand, such as a cursor on the screen, than when visual feedback was not provided [21,25]. Second, activation in LpIPS was greater during production with visual feedback of the form being produced than when visual feedback was not provided [22]. LpIPS involvement in production tasks, as reported by research with touchscreen-only tablets, appears to be strongly related to the use of visual feedback during motor movements. It is difficult to determine, however, whether LpIPS involvement is related to the use of visual feedback during production or to the somewhat artificial pairing between motor and visual experiences produced by touchscreen-only tablets.

1.2. The Current Study

Given that the meta-analyses conducted prior to the use of touchscreen-only tablets did not report any loci in posterior parietal cortex, and most reports that use touchscreen-only tablets report LpIPS involvement, we hypothesized that LpIPS involvement was due to the novel pairing among motor and visual experiences of production when using these tablets. We used data that were previously collected in [22] using the touchscreen-only tablet developed by Tam et al. [20] and data previously collected in Vinci-Booher and James [23] using the MRItab [24]. All participants were asked to produce letters to dictation using either the touchscreen-only tablet or the MRItab. Participants were also asked to perform two control tasks that allowed identification of responses associated with the visual-motor pairings that occurred with each tablet. We performed region of interest (ROI) analyses on three anatomically defined ROIs placed along the left intraparietal sulcus and three homologous ROIs in the right intraparietal sulcus. We expected that activation in LpIPS would be greater when participants were asked to produce letters using the touchscreen-only tablet than when they used the MRItab. Such a result would support our hypothesis that the LpIPS involvement observed in recent studies is related to the somewhat artificial visual-motor pairing that touchscreen-only tablets require.

2. Methods

Participants, materials, and procedures have been described in detail in Vinci-Booher et al. [22–24] and will be described here briefly.

2.1. Participants

Thirty-two literate, English-speaking adults were recruited through an in-house database and by word-of-mouth. All participants were right-handed and free of neurological trauma, developmental disorders, and MRI contraindications. All participants provided written informed consent according to the guidelines of the Indiana University Institutional Review Board and were compensated with a gift card. Four participants in the MRItab group were excluded due to an unacceptable amount of motion during the MRI scanning procedure. Fourteen participants were from the Touchscreen group (mean age = 20.1 years) and 14 were form the MRItab group (mean age = 20.2) (see *2.2.2.1 Touchscreen-only group* and *2.2.2.2 MRItab group* and Fig. 1). There were no differences between groups in educational attainment; all participants were either undergraduate or graduate students (randomly distributed between groups) at a four-year university.

2.2. Materials

2.2.1. Stimuli

A set of 12 single upper-case letters of the Roman alphabet were selected: A, B, C, D, G, H, J, L, Q, R, U, and Y. All letters were written in white on a black background with a pen width of 7 points within a box that subtended 10 by 10 degrees of visual angle. The size and form of the letter stimuli within this box differed from trial to trial given the self-produced nature of the written stimuli. Block instructions and letter-name dictations were pre-recorded from a female native English speaker.

[1] Another meta-analysis was conducted after the availability of touchscreen-only tablets that reports slightly difference results [26]. The meta-analysis in Yuan and Brown [26], however, did not consider studies that used touchscreen-only tablets separately from those that did not, making the results difficult to interpret in the context of the current study.

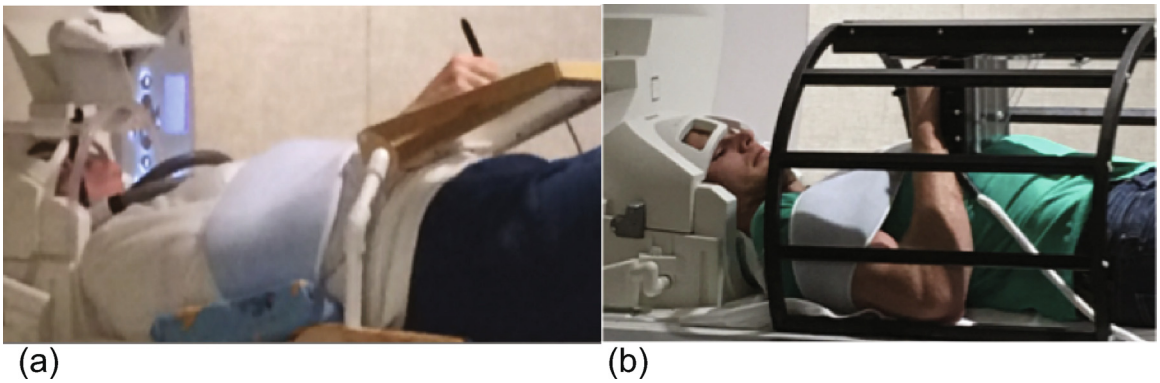

Fig. 1. Experimental Set-up for Touchscreen-only and MRItab groups. (a) Participants in the Touchscreen-only group were able to see their letter unfold in the mirror above their head as they produced it on the touchscreen surface. **(b)** Participants in the MRItab group were able to see their letter unfold on the MRItab surface as they produced it on the tablet surface.

2.2.2. Apparatuses

Participants in both conditions held an MR-safe stylus and wore a Wheaton® elastic shoulder immobilizer to restrict movement necessary for writing to elbow, wrist, and hand joints. Auditory instructions and letter-name dictations were presented through MR-safe headphones and Boom™ was used to enhance audio clarity. An in-house Matlab program using the Psychophysics Toolbox extensions interfaced with the headphones, projector, and either tablet to record and present all stimuli [2,14].

2.2.2.1. Touchscreen-only group.. Participants completed all tasks on a touchscreen-only, MR-safe writing tablet that records production trajectories and can be used to project the production trajectories onto a mirror above a participant's head as they produce the form [20]. A lap-desk kept the tablet in a fixed position near their torso so that they could locate and use the touchscreen with ease (Fig. 1). Participants in this group were able to see the letter unfold in the mirror as they produced it, but were unable to see their hands. All visual presentations were displayed onto a mirror attached to the head coil above the head of the participant with a Mitsubishi XL30 projector.

2.2.2.2. MRItab group.. Participants completed all tasks on the MRItab, an MR-safe tablet the records production trajectories and displays them onto a video display screen positioned directly behind the touchscreen surface [24]. The 'cage' apparatus kept the tablet in a fixed position near their torso. The head coil was tilted slightly so participants could see the tablet with ease (Fig. 1). Participants in this group were able to see the letter unfold on the tablet as they produced it; they were also able to see their hands. All visual presentations were displayed on the MRItab directly. Subject-specific adjustments to the exact location of the tablets ensured that participants were in a comfortable writing position and, in the case of the MRItab group, could easily see the tablet.

2.3. Procedures

All participants underwent a high-resolution anatomical scan followed by 4 fMRI experimental runs. During the fMRI runs, participants wrote letters with and without 'ink' and passively perceived their own handwritten letters dynamically unfold, resulting in 3 experimental conditions: Write Ink, Write No Ink, and Watch Unfolding. The Write Ink condition provided a direct pairing between visual and motor experiences during production with the MRItab but not with the Touchscreen-only tablet. The Write No Ink condition provided visual feedback of one's hand with the MRItab but not with the Touchscreen-only tablet; with neither tablet did it provide visual feedback of the form being produced. The Watch Unfolding condition provided the same visual feedback of the form being produced with both tablets.

Each run contained one block of each condition. Block orders were pseudo-randomized, as opposed to fully randomized, to ensure that the Write Ink condition occurred before the Watch Unfolding conditions in each run. Block orders were counterbalanced across participants and groups.

Each block consisted of 6 stimuli, one presented in each of the 6 trials within a block. The order of the six letters within each block was randomized. Each trial lasted 4 seconds. There was no gap between trials, resulting in 24-second-long blocks. Each block was separated by a 14-second inter-block interval, the last two seconds of which included auditory instructions for the next block. Auditory instructions were kept to a set of two simple one-word imperatives: "draw" and "watch". During the inter-block interval, only the fixation cross was visible in the mirror.

Each trial began with an auditory prompt that indicated the letter for that trial (e.g., "A" or "B"). During Write Ink and Write No Ink trials, the participant wrote this letter. During Watch Unfolding trials, participants passively watched a video of their own letter production unfold as if it were being written.

2.3.1. Scanning parameters

All neuroimaging was performed at the Indiana University Imaging Research Facility within the Department of Psychological and Brain Sciences. Specific parameters for anatomical and functional data collection for the Touchscreen group in [22] and for the MRItab group in Vinci-Booher and James [23].

2.4. Analyses

All neuroimaging analyses were conducted using Brain Voyager QX, Version 2.8 [4,10]. All statistical analyses were conducted using IBM SPSS Statistics for Mac OSX, version 25.

2.4.1. Preprocessing and motion correction

Preprocessing of functional data included slice scan time correction, 3-D motion correction using trilinear/sinc interpolation, and 3D Gaussian spatial blurring with a full-width-at-half-maximum of 6 mm. Temporal high-pass filtering was performed using a voxel-wise GLM with predictors that included a Fourier basis set with a cut-off value of 2 sine/cosine pairs and a linear trend predictor. Individual anatomical volumes were normalized to Talairach space Talairach & Tournoux, 1988. Coregistration of functional volumes to anatomical volumes was performed using a rigid body transformation.

2.4.2. ROI analyses

Region of interest (ROI) analyses were performed using the peak

Table 1
Range of Talairach Coordinates for ROIs

Participant Group	ROI	x-range [min, max]	y-range [min, max]	z-range [min, max]
Touchscreen-only	LaIPS	[-55, -32]	[-43, -23]	[27, 54]
	LmIPS	[-45, -21]	[-52, -33]	[29, 54]
	LpIPS	[-35, -17]	[-65, -43]	[29, 53]
MRItab	LaIPS	[-48, -26]	[-46, -26]	[35, 60]
	LmIPS	[-45, -22]	[-60, -36]	[31, 57]
	LpIPS	[-40, -17]	[-67, -47]	[32, 53]

Some variability is expected due to individual variability in IPS anatomy.

percent BOLD signal change from three anatomically localized 10 mm^3 ROIs in the left intraparietal sulcus during the Write Ink, Write No Ink, and Watch Unfolding conditions: left anterior IPS (LaIPS), left middle IPS (LmIPS), and left posterior IPS (LpIPS). We also selected three homologous regions in the right hemisphere (see Supplementary Materials).

Individual participant ROIs were placed based on their anatomical image in Talairach space. Anatomical locations were determined by, first, referencing the Talairach Daemon and, second, confirming the location by referencing the Duvernoy (1999) human brain atlas to verify. This two-step process was necessary because the Talairach Daemon does not provide anatomical labels for the sulci and, additionally, the correspondence between the anatomy and anatomical labels in the Talairach Daemon can be misaligned during the normalization procedure. Talairach coordinates for each ROI in each participant are presented in Table 1 and probability maps for the placement of each ROI are displayed in Fig. 2.

We performed 3 Two-Way Mixed Measures ANOVAs for each hemisphere—one for each condition—for a total of 6 tests. Each ANOVA contained 2 factors: TABLET, ROI. TABLET had two levels: Touchscreen-only, MRItab. ROI had three levels: aIPS, mIPS, pIPS. A Bonferroni correction for multiple comparisons for $p = 0.05$ resulted in a significance criterion of $p < 0.008$ for each ANOVA.

Data points that were 3 standard deviations away from the within-condition, within-group mean were considered outliers and were removed prior to each ROI analysis. This entailed the removal of data from one participant in the MRItab group from the Write Ink and Write No Ink conditions. ROI analyses for Write Ink and Write No Ink conditions, therefore, included 14 participants in the Touchscreen-only group and 13 participants in the MRItab group. ROI analyses for the Watch Dynamic condition included 14 participants in each group.

3. Results

3.1. Write Ink

A Two-Way Mixed Measures ANOVA revealed a main effect of ROI, $F(2, 50) = 7.33$, $p = .002$, and an interaction between ROI and TABLET, $F(2, 50) = 5.88$, $p = .005$ (Fig. 3). The main effect of TABLET was not significant, $F(1, 25) = 1.052$, $p = .315$. Activation in LpIPS was higher when participants used the touchscreen-only tablet (M = 1.13, SE = .74) than when they used the MRItab (M = .71, SE = .33), $t(25) = 2.130$, $p = .043$. There were no between-tablet differences in LaIPS activity, $t(26) = .702$, $p = .489$, or LmIPS activity, $t(26) = .630$, $p = .534$.

There was a significant linear relationship among the ROIs when participants used the MRItab, $F(1, 25) = 11.335$, $p = .002$, that was not apparent when participants used the touchscreen-only tablet, all $p > .80$. When participants used the MRItab, the LaIPS ($M = 1.21$, $SE = 0.08$) and LmIPS ($M = 1.10$, $SE = 0.06$) were both more active than the LpIPS ($M = 0.94$, $SE = 0.09$), $t(26) = 2.079$, $p = .048$; $t(26) = 2.846$, $p = .009$. The difference between LaIPS and LmIPS did not reach significance, $t(27) = 1.759$, $p = .090$.

3.2. Write No Ink

A Two-Way Mixed Measures ANOVA revealed a main effect of ROI, $F(2, 50) = 10.27$, $p = .000$. The main effect of TABLET was not significant, $F(1, 25) = 0.440$, $p = .513$. The interaction between ROI and TABLET was not significant, $F(2, 50) = 1.58$, $p = .217$ (Fig. 4).

The main effect of ROI was due to a significant linear relationship among ROIs, $F(1, 25) = 15.227$, $p = .001$, that did not differ between tablets. The LaIPS ($M = 1.08$, $SE = 0.06$) and LmIPS ($M = 0.92$, $SE = 0.07$) were both more active than the LpIPS ($M = 0.80$, $SE = 0.08$), $t(26) = 3.754$, $p = .001$; $t(27) = 2.572$, $p = .016$. The difference between LaIPS and LmIPS did not reach significance after correction for

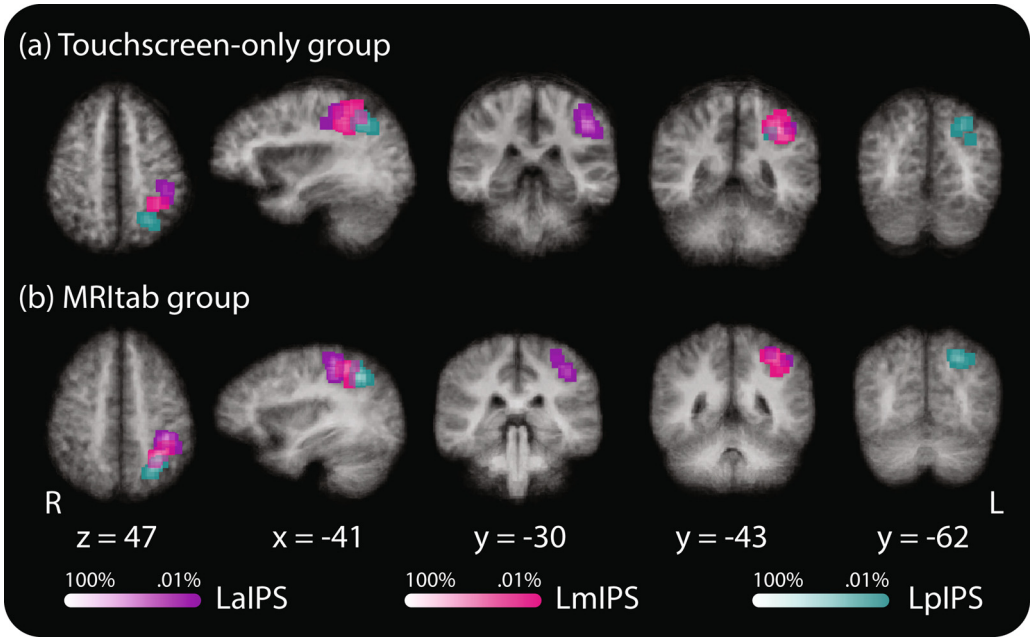

Fig. 2. Probability map for three regions of interest (ROIs) displayed on a group averaged anatomical image. Percentage values correspond to the percentage of participants in a particular group whose ROI placement included that voxel.

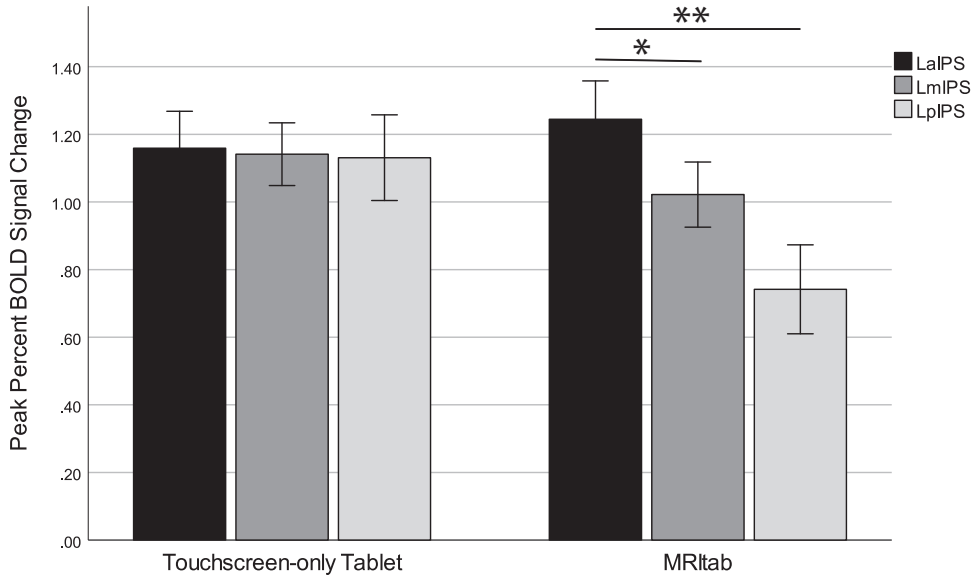

Fig. 3. Peak Percent Bold Signal Change in Left IPS ROIs During Write Ink, * $p < .05$, ** $p < .01$.

multiple comparisons, $t(26) = 2.495$, $p = .019$.

3.3. Watch Unfolding

A Two-Way Mixed Measures ANOVA revealed no significant effects: ROI: $F(2, 52) = 1..256$, $p = .293$; TABLET: $F(1, 26) = 1.696$, $p = .204$; ROIxTABLET: $F(2, 52) = .072$, $p = .931$.

4. Discussion

The availability of touchscreen-only MR-safe tablets has made it possible for researchers to provide real-time visual feedback during symbol production. The visual feedback provided by these tablets is projected onto a mirror above the participants' heads while they write on the touchscreen near their torso. We compared production with a touchscreen-only tablet [20] and production with a touchscreen-and-display tablet [24] to determine if the unnatural spatial pairing (non-visually guided) between the motor and visual components of production that occurs with touchscreen-only tablets was related to recent findings concerning the recruitment of parietal cortex during production. We found that parietal involvement in production tasks, especially LpIPS involvement, was affected by the pairing between motor and visual components of production. LpIPS involvement was dependent upon whether or not participants were able to see their hand and production on the same surface where they were producing it. These findings have implications for inferences from studies using touchscreen-only MR-safe writing tablets and for our understanding of parietal involvement in production tasks.

4.1. Left Anterior Intraparietal Involvement in Production

Our results are consistent with meta-analyses of the neural systems supporting production [15,16] as well as more recent works using touchscreen-only MR-safe tablets [5,6,12,21,22,25] that suggest that LaIPS activation during production is related to the motor component of production—the hand movements required to produce the desired form. LaIPS activation during production was not reliant upon visual feedback: LaIPS was more active than LmIPS and LpIPS during production with ink and during production with 'no ink' when participants used the MRItab. This relationship did not occur during passive perception of the letters unfolding, suggesting that greater recruitment of LaIPS occurred in conditions that required a motor movement. We,

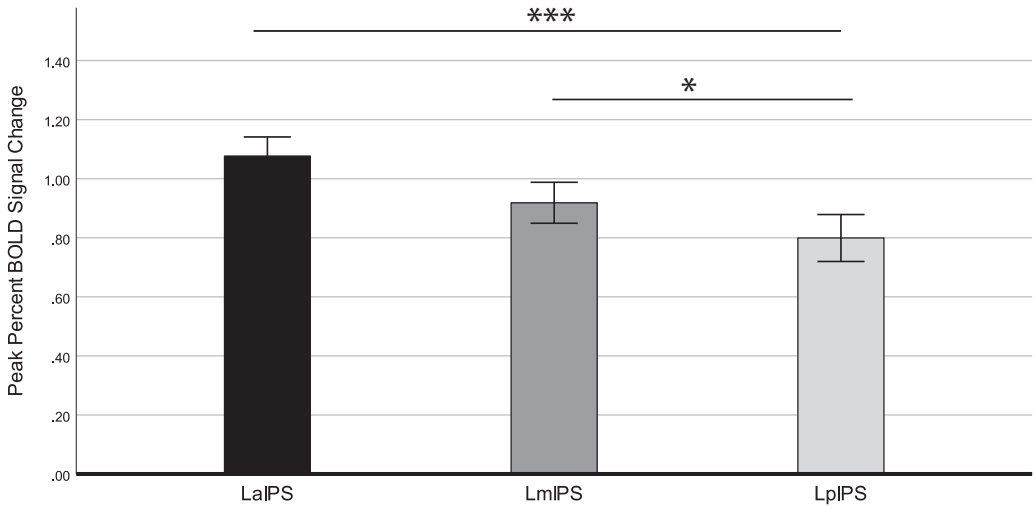

Fig. 4. Peak Percent Bold Signal Change in Left IPS ROIs During Write No Ink, * $p < .05$, *** $p < .001$.

furthermore, found no between-tablet differences in LaIPS activation during production or during production with no ink.

4.2. Left Posterior Intraparietal Involvement in Production

Our results suggest that the findings concerning LpIPS involvement in production were related to the unusual production experience required by touchscreen-only MR-safe writing tablets. We found a linear relationship among the left hemisphere ROIs when participants used the MRItab that was not apparent when participants used the touchscreen-only tablet. Follow-up comparisons revealed that the difference in linear relationship between tablets was driven by differences in LpIPS activity. Only the LpIPS differed between tablets. Activity in LpIPS during production was greater when participants used the touchscreen-only tablet than when they used the MRItab; however, activity in neither the LaIPS nor the LmIPS was significantly different when participants used the touchscreen-only tablet than when they used the MRItab. These results are consistent with two meta-analyses on production that were conducted across a wide array of experimental setups that were available prior to the use of touchscreen-only writing tablets that report no posterior parietal loci [15,16].

The production experience required by the touchscreen-only tablet was unusual in at least two respects. First, unlike the MRItab, participants were not able to see their hand during production with the touchscreen-only tablet. The results of the production with 'no ink' condition, however, suggest that the difference in LpIPS activation cannot be attributed to whether or not participants were able to see their hand alone. When producing letters with 'no ink' using the touchscreen-only tablet, the visual feedback was simply a blank screen. When using the MRItab, the visual feedback was a blank screen but also one's hand moving in the necessary stroke pattern. If activation in LpIPS were dependent only upon whether or not participants were able to see their hand during production, then we would expect to see a difference in LpIPS activation between the touchscreen-only tablet and MRItab during production with 'no ink'. It may still be that the differences were related to whether or not they were able to see their hand *and* the visual feedback on the writing surface, but it is unlikely that between-tablet differences in LpIPS activation were related to whether or not participants were able to see their hand alone.

Second, the motor and visual components of production occur at different spatial locations with the touchscreen-only tablet, but they occur at the same spatial location with the MRItab. The unusual spatial pairing between hand movements and visual feedback may have led to greater activation in LpIPS during production with the touchscreen-only tablet than during production with the MRItab. It is unlikely that between-tablet differences in LpIPS activity were related only to the location of the visual feedback because we observed no significant differences during the Watch Unfolding condition.

Visual feedback of the form being produced during production is typically experienced on the writing surface itself. Production episodes that violate the expected contingency between motor movements and visual feedback may lead to different neural responses than typical production episodes. The possible reason that such visual-motor violations might lead to a greater recruitment of LpIPS and right intraparietal sulcus than expected visual-motor contingencies are many (e.g., greater effort, greater visual attention, remapping of motor and visual space, etc.) and should be the topic of future research.

CRediT authorship contribution statement

Sophia Vinci-Booher: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Karin H. James:** Methodology, Resources, Data curation, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

This report makes use of an MRI-compatible device that is patent pending. If a patent issues it will be owned by the Trustees of Indiana University. The authors, therefore, believe there is no conflict of interest to report.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.neulet.2020.134920.

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